5th International Conference on Experimental Fluid Mechanics – ICEFM 2018 Munich
Munich, Germany, July 2-4, 2018

A method for vortices identification in wall-bounded turbulent flows

Kangjun Wang[1], Zhanqi Tang[1,2], Nan Jiang[1,2]

[1] Department of Mechanics, Tianjin University, Tianjin, China
[2] Tianjin Key Laboratory of Modern Engineering Mechanics, Tianjin, China
kangjunwang@foxmail.com, zhanqitang@tju.edu.cn, nanj@tju.edu.cn

Abstract

The distinction of impact on vorticity between shearing motion and swirling motion is analyzed, then the standard deviation of angle velocity of surrounding points around question point is proposed to represent strength of shearing motion. A new vortices identification method called R_{st}-method is proposed based on the ideas that angle velocity of surrounding points around question point induced by shearing motion were uneven. Comparison of the new method with the swirling-strength method is conducted, the consequence indicates that the new method could well capture all various strength vortices in wall-bounded turbulent flows.

1 Introduction

Organized coherent structures dominate the generating and maintaining of turbulent Reynolds stress in the wall-bounded turbulent flows, though the exact mechanism of their evolution process are still confusing but it is widely accepted that various scale and evolution stage of hairpin-sharped vortices are the main constituent of the coherent structures (Adrian, 2007; Stanislas et al., 2008). Therefor the identification of these vortices is a critical link to observe and understand their dynamic properties, and analyse interaction between vortices and surrounding fluid in velocity field of wall-bounded turbulent flows. Since the precise definition of vortices as yet existing argument, the properties of vortices frequently be qualitatively characterized. Robinson proposed a generally accepted intuitive definition of vortices : A vortex exists when instantaneous streamlines mapped onto a plane normal to the vortex axis exhibit a roughly circular or spiral pattern, when viewed from a reference frame moving with the center of the vortex core (Robinson, 1991). The foregoing definition containing two essential conditions : A convectional reference frame and a roughly circular or spiral pattern, requires a priori Galilean convention velocity.

Traditionally, in the Eulerian frame vorticity has been utilized to identify the core of vortices, as it represent the average angular velocity of fluid element, and the core of vortices are thought of the regions which have highlight values of vorticity (Kim et al., 1987; Provenzale, 1999). However, because of the vorticity generated by velocity gradient of shearing motions, the method using vorticity to identify the vortices would yield a misleading result (Jeong and Hussain, 1995), i.e. the regions with no rotational motion such as laminar boundary layer have prominent vorticity. Hence, many researchers have proposed other approaches to identify the vortices, such as Q criterion (Hunt et al., 1988) and λ_{ci} criterion (ZHOU et al., 1999).

This paper propose a new method based on topological property of vortex for vortices identification in wall-bounded turbulent flow. In order to distinguish the swirling motion from the intense shearing motion within turbulent boundary layer, the new method used parameter R_{st} as the threshold to filter shearing motion.

2 New vortex identification method

In the turbulent flow field measured by 2D-TRPIV, vorticity was defined as $\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$, the discrete formation of which was $\omega_{i,j} = \frac{v_{i+1,j} - v_{i-1,j}}{2\Delta x} - \frac{u_{i,j+1} - u_{i,j-1}}{2\Delta y}$. As show in figure.1, vorticity of fluid field at point **A** means the total angle velocity of four surrounding point (**B**, **C**, **D**, **E**) around the given point **A**, or total angle velocity of two mutually orthogonal line segments L_1 and L_2 (i.e. **BD** and **EC**) going through the given point A(i, j), so $\omega_{i,j} = \omega_1 + \omega_2$, where ω_1 and ω_2 denote angle velocity of L_1 and L_2 around point **A**. Unlike the swirling motion made all of two line segments had the same angle velocity, the shearing motion would lead difference of angle velocity between the two line segment, i.e. $\omega_1 \neq \omega_2$. When the direction of shearing motion parallel a line segment, the shearing motion would have no impact to this line segment, on the contrary, another line segment would be affected intensely.

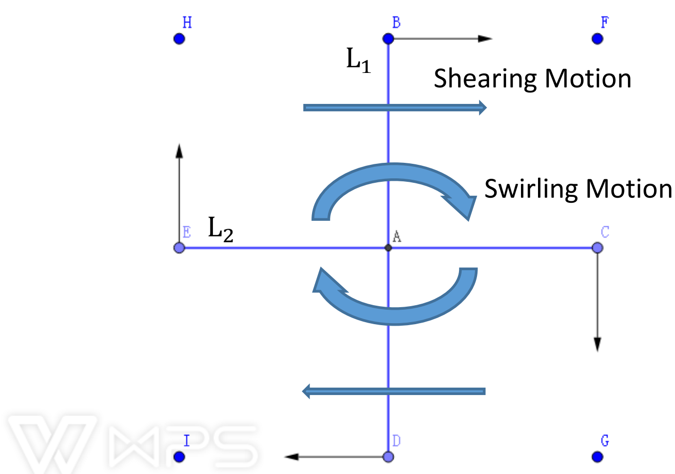

Figure 1: Qualitative model of vorticity.

Based on the idea of that the shearing motion would lead to the angle velocity disequilibrium of line segments in different direction, we introduced stand standard deviation of angle velocity of line segments **S** in different direction to represent strength of shearing motion at point.

$$S = \sqrt{\frac{1}{n}\sum_{r=1}^{n}(\omega_r - T)^2} \tag{1}$$

$$T = \frac{1}{n}\sum_{r=1}^{n}\omega_r \tag{2}$$

Where ω_r represent angle velocity of line segment L_r, note that, the angles between the line segments and X-axis were distributed evenly over [0, 2π], for instance, as show in figure.1, when $n = 4$ the L_1,

L_2, L_3, L_4 represents line segment **BD**, **HG**, **EC** and **IF** respectively. Then in order to distinguish the swirling motion from the intense shearing motion the parameter R_{st} was introduced as given below:

$$R_{st} = \begin{cases} sign(T) * \left(1 - \frac{S}{|T|}\right) & , \quad \frac{S}{|T|} < a \\ 0 & , \quad \frac{S}{|T|} \geq a \end{cases} \tag{3}$$

Where the parameter **a** was a threshold level, empirically **a**=0.55 when **n**=4 can make the scalar field of R_{st} highlight the vortices core. As **S** means the shearing vorticity, **T** means total vorticity, hence R_{st} represent the ratio of vortical vorticity over total vorticity. At present, this new method mainly be used to identify vortices in 2D velocity field of turbulent flow measured by 2D-TRPIV.

3 Applications of the new method

The identification of vortices in wall-bounded turbulence flow is an important application of vortices identification method. For testing the performance of new method, a set of experimental PIV data of turbulent boundary layer were used in this section to examine the ability of this new method identifying vortices. Detailed imformation about this experimental data can be found in (Tang et al., 2017). Figure.2 shows the one Galilean-decomposed instantaneous velocity field and streamline with a

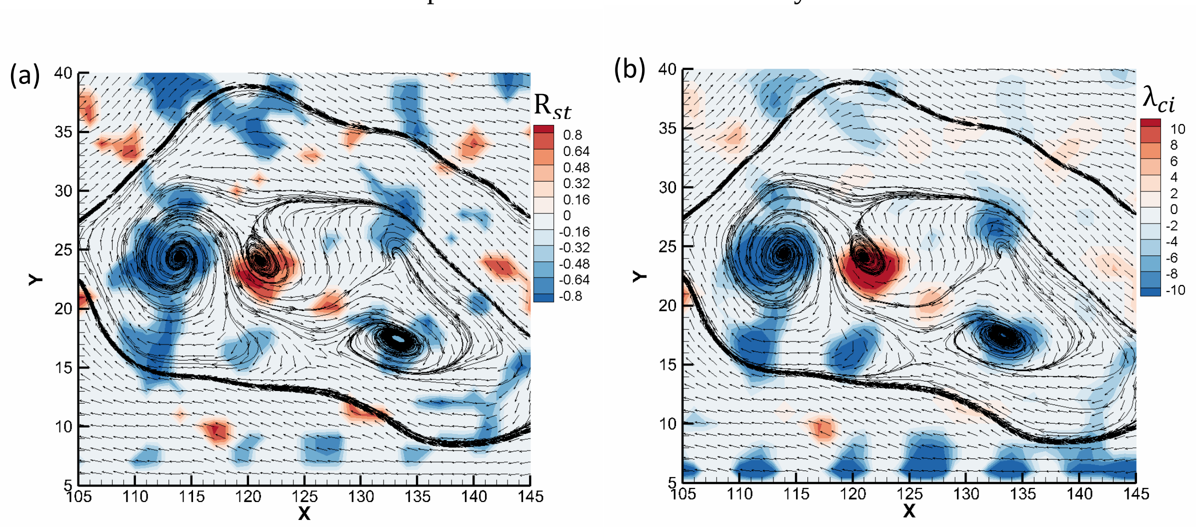

Figure 2: Comparison of (a) R_{st} field and (b) λ_{ci} field.

constant convection velocity $U_c = 0.8U_\infty$, where U_∞ was the velocity of free stream, contours of the R_{st} and λ_{ci} were shown in the background. For R_{st} field calculation we selected **a**=0.55 and **n**=4, from figure.2 we can see that R_{st} field can effectively identify the vortices, and comparing to λ_{ci} the R_{st} has constant variation range, so it can clearly highlight vortices with different strength, while the value of λ_{ci} is very low at the vortices with weak strength which may be ignore in most case.

4 Conclution

The impact of shearing motion to vorticity in different orientation were different, consequently, the angle velocity of surrounding points around question point induced by shearing motion were uneven in different directions. for instance, when the shearing motion parallel the X-axis in Cartesian coordinates, the surrounding points around question point in vertical direction would get maximum angle velocity by effect of shearing motion, while the surrounding points around question point in horizontal direction could not be impacted by shearing motion. While the angle velocity of surrounding points around question point induced by swirling motion were uniform in all directions, hence the standard deviation of angle velocity of surrounding points around question point represented strength of shearing motion. Base on the above analysis, a new parameter R_{st} was introduced to represent the ratio of vortical vorticity and total vorticity. As the vortical vorticity was closely related to vortices, hence the field of R_{st} could be used to identify the vortices. It was found that the a=0.55 when n=4 could well capture the vortices in turbulent boundary layer for cases we studied. Comparing to λ_{ci} the R_{st} has constant variation range [-1, 1], so it can clearly highlight vortices with all various strength.

Acknowledgements

This work is supported by NSFC with Grant No. 11332006, 11732010, 11572221, 11502066.

References

Adrian, R. J. (2007). "Hairpin vortex organization in wall turbulence." Physics of Fluids **19** (4): 041301.

Hunt, J. C. R., A. A. Wray and P. Moin (1988). Eddies, streams, and convergence zones in turbulent flows. Center for Turbulence Research Report. **CTR-S88**.

Jeong, J. and F. Hussain (1995). "On the identification of a vortex." Journal of Fluid Mechanics **285** (-1): 69.

Kim, J., P. Moin and R. Moser (1987). "Turbulence statistics in fully developed channel flow at low Reynolds number." Journal of Fluid Mechanics **177** (-1): 133.

Provenzale, A. (1999). "TRANSPORT BY COHERENT BAROTROPIC VORTICES." Annual Review of Fluid Mechanics **31** (1): 55-93.

Robinson, S. K. (1991). "Coherent Motions in the Turbulent Boundary Layer." Annual Review of Fluid Mechanics **23** (1): 601-639.

STANISLAS, M., L. PERRET and J. FOUCAUT (2008). "Vortical structures in the turbulent boundary layer: a possible route to a universal representation." Journal of Fluid Mechanics **602**.

ZHOU, J., R. J. ADRIAN, S. BALACHANDAR and T. M. KENDALL (1999). "Mechanisms for generating coherent packets of hairpin vortices in channel flow." Journal of Fluid Mechanics **387**: 353-396.

Tang, Z., Y. Wu, Y. Jia and N. Jiang (2017). "PIV Measurements of a Turbulent Boundary Layer Perturbed by a Wall-Mounted Transverse Circular Cylinder Element." Flow, Turbulence and Combustion.